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STRUCTURAL RESEARCH SERIES NO. 427

BOND CHARACTERISTICS OF MODEL REINFORCEMENT

By
NANCY L. GAVLIN

A Report on a Research
Project Sponsored by
THE NATIONAL SCIENCE FOUNDATION
Research Grant ATA 7422962

UNIVERSITY OF ILLINOIS
at URBANA-CHAMPAIGN
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1. INTRODUCTION

1.1 Object and Scope

The purpose of this investigation was to study the bond characteristics of #8 gage steel reinforcing wire embedded in small-scale concrete.

The investigation included a total of seven series of pull-out tests, with eight pull-out specimens tested per series. The program of testing is outlined below.

Bond Length (in)	Plain Wire	Knurled Wire
1	Series III Series IV	Series I Series II
3		Series V Series VI
6		Series VII

1.2 Bond Between Steel and Concrete

Because of the difficulty in controlling the many variables involved in an experimental study of bond characteristics, and the fact that the sources of bond are microscopic in nature, the understanding of the nature of bond is incomplete. However, based on experimentation and theories on friction, a hypothesis has been developed which states that the bond of wire is caused by two distinct mechanisms: (1) an initial interlocking mechanism and (2) a sliding friction mechanism (Abrams, 3).

When steel wire is cast in concrete a continuous contact is formed between the two materials. An intense interlocking exists between these two materials as a result of a physical interlocking caused by the roughness of the surface of the steel, and a chemical interlocking formed when the cement paste penetrates the oxide layer of the steel. When a force is applied parallel to the plane of contact, the concrete (because it is the weaker material) will shear through a plane determined by the peaks of the surface of the steel wire. For this reason, a certain definite bond force can be applied before any measurable slip will take place.

After the initial shear failure of the concrete occurs, the indentations of the surface of the steel will still be filled with concrete so that a rough contact surface of concrete on concrete remains. Further slip, therefore, becomes a problem of sliding friction. When two rough surfaces come into contact with each other they will only actually be in contact at certain points (called junctions). The summed area of the junctions is usually small compared to the apparent area of contact. If a lateral force (such as shrinkage pressure) exists at this surface of contact, motion between the two surfaces can occur only if the frictional resistance is overcome. The frictional resistance is determined by the shear strength of the junction.

While both bond mechanisms are related to the shear strength of the concrete, the areas to be sheared are different for each case. During the interlocking phase, the area of shear is determined by the roughness of the steel surface. During the frictional phase, the area of shear is determined by the lateral force. Once the interlocking mechanism has failed, it can not be remobilized. However, the sliding friction mechanism continuously repeats itself as new contact surfaces are constantly being formed.

Reference will be made to these mechanisms of bond in the discussion of the test results obtained in this investigation.

1.3 Acknowledgments

This report was written under the supervision of Dr. M. A. Sozen, Professor of Civil Engineering. This study was supported by the National Science Foundation Grant ATA 22962.

Acknowledgment is due to Mr. J. N. Sterner for the help he provided in the operation of the MTS hydraulic testing equipment.

2. TEST PROCEDURE

2.1 Test Specimen

The pull-out test specimen consisted of a steel reinforcing wire embedded in a 4 x 4 x 9 in. rectangular concrete prism. The steel wire was centered in the prism and oriented with the length of the wire parallel to the nine-in. length of the prism. The actual bond length of the steel wire was varied by pulling thin-walled plastic tubing over the portion of the wire which was not to be bonded with the concrete (See Figure 2.1).

2.2 Steel Wire

The steel used was #8 gage (0.162 in. diameter) black annealed wire. The wire was reannealed at a temperature of 900° F for 2 hours, giving it a yield stress of approximately 70 ksi.

The steel wire was knurled with a specially built machine in the laboratory. The machine consisted of a motor and two sets of knurling disks. The first set of disks are rotated by the motor. The disks knurl two diametrically opposite sides of the bar as well as propelling the bar through the second set of disks which knurl the bar on sides 90° from the previously knurled sides. The finished wire has four strips of knurls running the length of the bar. The depth of the knurl was measured by Staffier (1) with the use of a stereo microscope and found to range between 0.0035 and 0.005 in. The longitudinal spacing of the knurl was found to range between 0.028 and 0.032 in.

2.3 Plastic Tubing

Acrylic plastic tubing with a 3/8-in. outside diameter and a 1/16-in. thick wall was used to control the bonded length of the wire. One piece of tubing was drawn over each end of the wire, leaving a gap at the middle of the wire equal to the desired bonded length. The clearance between the walls of the tubing and the steel wire was sealed with silicone rubber bathtub caulk. Since the clearance between the plastic tubing and the wire was enough (inner diameter of tubing 0.25 in. compared with wire diameter of 0.16 in.) to preclude interference between the two during testing, the plastic tubing was not removed when the forms were struck. It was the intention that this would minimize disturbance of the concrete during setting.

2.4 Concrete

The proportions of the concrete mix, (given in ratios of cement: fine sand:coarse sand by weight) were 1:0.95:1.38. Universal Atlas high early strength (type III) Portland cement was used with a water:cement ratio of 0.80. The fineness moduli of the fine sand and coarse sand were 0.843 and 2.61 respectively. Results of a sieve analysis for each type of sand are presented in Table 2.1.

The compressive and splitting strengths of the concrete were determined from tests on 4 by 8-in. cylinders. The results of these tests are summarized in Tables 2.2 and 2.3, and a plot of splitting strength vs. compressive strength is shown in Figure 2.2.

2.5 Casting and Curing

The steel wire was first cleaned with a solvent and acetone to remove any grease and dirt from its surface. The plastic tubing was then pulled over the wire to the desired bonded length and the ends of the tubes, adjacent to the bonded portion of the wire, were sealed.

The specimens were cast horizontally in steel forms with the wire (with the plastic tubing) held in its proper position by clamping devices on the end plates of the forms. Four inches of wire extended from each end of the form.

Eight pull-out specimens along with ten 4 x 8-in. cylinders (to be used in determining the compressive and splitting strengths of the concrete) were cast per batch of concrete. The pull-out specimens were vibrated on a vibrating table. The test cylinders were vibrated with an interior vibrator.

The specimens and cylinders were left in their forms overnight, covered with sheet plastic to retain their moisture. After one day the forms were struck and the specimens were wrapped in wet burlap, with plastic sheeting covering the burlap. Finally, at the end of one week the burlap and plastic were removed and the specimens were left at room temperature and humidity until the time of testing.

2.6 Testing

The pull-out tests were carried out on an MTS high-response, closed-loop electrohydraulic materials test system. The capacity of the loading frame and ram, for the system used, is 50 kips. The machine was operated through a control module that is part of a closed loop system having the capability of controlling load, stroke or strain. The stroke sensitivity is $\pm$ 0.0001 in. and the load sensitivity is .1% of the load at full capacity.

During the pull-out tests the stroke control option was implemented. All of the tests were run at a rate of stroke of 0.0005 in./sec.

The test specimens were placed in a steel cage. The top of the cage was gripped, through a hinge, by the upper head of the testing machine. The bottom seat of the cage had a hole in it, through which the steel wire was placed to be gripped by the lower jaw grips of the testing machine (see Fig. 2.3).

Slip of the reinforcing wire was measured with an LVDT (Linear Variable Displacement Transducer). The LVDT has a sensitivity of .1% of the full travel (full travel is 0.025 in.). It was held by a heavy metal ring which rested on the top surface of the concrete prism, and was kept in contact with the free end of the steel. The LVDT, therefore, recorded the slip of the steel at the end of the bonded length versus the top surface of the concrete prism.

Curves of load vs. slip were plotted by an x-y plotter. For each test two plotters were used, one which displaced an inch per 0.0001 in. of slip and the other which displaced an inch per 0.001 in. of slip. Slip measurements were stopped at 0.015 in.

3. DESCRIPTION AND INTERPRETATION OF RESULTS

3.1 Presentation of Results

The material properties of the test specimens and all of the test results are summarized in Tables 3.1, 3.2, 3.3 and 3.4, and are graphically summarized in Figs. 3.1, 3.2, 3.3 and 3.4. In some instances, the bond strength is defined in terms of bond force, and in some instances, in terms of bond stress. Bond stress is used where it will facilitate comparisons of bond strength for various bonded lengths. Bond stress is defined as the bond force divided by the surface area of the bonded length of wire. Because of mechanical difficulties with the plotters, graphs of bond force vs. slip were not recorded for every test conducted.

3.2 Results of Test Series I, II, III and IV

The results of Series I and II (one-in. bonded length, knurled) are plotted in Figure 3.1, and the results of Series III and IV (one-in. bonded length, plain) are plotted in Figure 3.2. The typical characteristics of these bond stress-slip relationships tend to support the hypothesis suggested in section 1.2 of this report. The bond stress initially increased to a peak value at a measured displacement of about 0.0001 in. At this point the bond stress dropped, accompanied by a large slip. The initial portion of the curve represents the initial interlocking bond mechanism. Although this mechanism does not account for any slip of the wire, an apparent slip of about 0.0001 in. was measured. However, this is very small compared with the slips measured after the peak value of bond stress was reached, and could be the result of distortion in the system. The abrupt change in bond stress, which follows the peak bond stress, suggests that the interlocking mechanism has failed and the sliding friction mechanism has taken over.

While the general trends of the test results for Series I, II, III and IV are very similar, differences between Series I and II (knurled), and Series III and IV (plain) do exist. The mean values for both the peak stress and the frictional resistance stress are higher for the knurled wire than for the plain wire. Considering the coefficient of variation of the data (Table 3.3) involved in the pull-out tests, and the amount of overlap of the test values for the peak bond stresses of the knurled and the plain wire, no decisive conclusions can be drawn concerning the effect of knurling on the peak bond stress. This overlap of values, however, does not occur for the frictional resistance bond stress (Table 3.4). Therefore, knurling does seem to influence the magnitude of the bond stress at this stage. Frictional resistance is determined mainly by the shear strength at the junctions. However, for extremely rough surfaces (like that produced by knurling), one surface may have to be lifted over the other one as a kind of interlocking takes place. In this case the frictional resistance increases. In several of the tests conducted in this investigation the initial frictional resistance stress, for the knurled wires, increased to a value greater than the peak bond stress of the initial interlocking phase.

The bond stress-slip curves actually appear to have three phases, with a transition zone appearing between the initial interlocking phase and the final frictional resistance phase. During the frictional resistance phase, the bond stress continues to decrease at a very slow rate. This further reduction in bond stress is the result of a loss of contact stress, as outlined by Stocker (2). The shearing of the interlocking keys results in the formation of loose wear particles. Through displacements of the contact surfaces, the wear particles are rearranged into a more dense configuration, resulting in a reduction in volume. This reduction in volume at the contact surface leads to a decrease in contact pressure.

The results of the first four series of pull-out tests exhibit a large range of bond stress-slip relations. This is due to the fact that it is very difficult to control the test conditions at the concrete-steel interface. Minute variation of the surface of the steel, such as variation in the depth of the knurl or the diameter of the wire, will result in measurable variations of bond stress. In addition, the consistency of the concrete at the steel-concrete interface can be highly variable from specimen to specimen. The distribution of air voids and aggregates, and the degree of bleeding will all influence the strength of the bond.

3.3 Results of Test Series V, VI and VII

The results of Test Series V and VI are plotted in Figure 3.3, and the results of Test Series VII are plotted in Figure 3.4. These plots suggest that the peak bond stress decreases with increasing bonded length. Since the bond force of the one-in. specimen is not constant for all values of slip, but rather decreases with increasing values of slip, it should be expected that the bond stress should decrease with increasing bonded length.

The plots of Test Series V, VI and VII exhibit an initial phase, where a peak bond stress is reached at a very small amount of slip. However, there is no sudden drop in the bond stress immediately after the initial peak stress is reached. This behavior may be explained in terms of the longer bonded lengths. For a longer bond length there is a greater chance for wedging action to occur as a result of variations in the diameter and placement of the steel wire. Also, since the peak bond stress should decrease for increasing bond lengths, while the frictional resistance should remain very nearly constant, the difference between the peak stress and the frictional resistance should be less for greater bonded lengths. Finally, for a very short bond length, the initial failure will occur simultaneously at every point along the bonded length. This will result in a sudden drop in bond stress. For a longer bond length, however, the initial failure will occur gradually along the bonded length.

The results of these last three series of pull-out tests exhibit a large range of bond stress-slip relations. This occurs for the same reasons as those described in the previous section.

3.4 Calculation of Bond Force-Slip Relationships

Theoretically, given a bond force-slip curve for a one-in. bond length, projections of bond force-slip relations over any given bond length can be determined. The calculations for these projections are based on the following three assumptions (Stocker (2)):

1. The change in slip over any bonded length is equal to the change in length of the steel (the deformation of the concrete is considered negligible).
2. The change in steel force over a given bonded length is equal to the bond force transferred to the concrete.
3. The bond force-slip relation in the one-in. pull-out test represents the actual bond slip relation between the wire and the concrete.

The first step in determining a bond force-slip relation for a specific bonded length is to calculate the bond force as a function of bonded length, for several trail end (unloaded end) slips.

This calculation is an iteration procedure. The bonded length is divided into small iteration intervals and the iteration is begun at the unloaded end of the bonded length, where the slip and steel stress are known. The procedure is:

1. Assume a strain at the interval.
2. Based on assumption (1) and an assumed value for the slip at the unloaded end, calculate the slip at the end of the interval.
3. From the given bond force-slip relationship for the one-in. bond length, determine the bond force corresponding to the calculated slip. The bond force is considered to be constant along the interval.
4. Based on assumption (2), compute the strain for the interval.
5. Compare the value of strain claculated in step 4 with the value assumed in step 1.

The values of strain and slip found for the end of the first iteration interval are next used as the known values at the beginning of the second interval and then the iteration procedure is repeated. This process is continued until the sum of the iteration intervals equals the desired bonded length.

Once the bond force vs. bonded length relationship has been calculated for several trail end slips, it is possible to construct bond force-slip curves for any bonded length. These relationships are illustrated in Figures 3.5 and 3.6.

The bond force vs. bonded length calculations were made with the aid of a computer. A copy of the program used is included in Appendix A.

How these calculations apply to this investigation, will now be discussed. This discussion will be limited to the results of tests on the knurled wire (Test Series I, II, V, VI and VII).

In order to apply this procedure, representative curves must be chosen for the bond force-slip relationships measured in tests with bonded lengths of 1,3 and 6 in.

Despite the large amount of scatter of the test results within each series of tests, the test results for the 3-in. bonded length specimens (Test Series V and VI) definitely fall into two distinct groups of bond stress-slip relationships. The differences in the bond forces measured for these two series, therefore, seem to be the result of some systematic difference rather than the result of the random variabilities of the specimen properties.

A plot of maximum bond stress vs. compressive strength of the concrete (Figure 3.7) reveals no specific relationship between these two properties of the test specimen. However, in a plot of bond stress vs. splitting strength of the concrete (Figure 3.8), there seems to be a trend indicating that the bond stress decreases with decreasing splitting strength. A review of the plot of splitting strength vs. compressive strength of the concrete (Figure 2.2) further indicates that the concrete strengths of Test Series V and VII do not fall within the same range of concrete strengths as those of Test Series I, II and VI. Furthermore, the summary of compressive and splitting strengths of the concrete for each test series, given in Tables 2.2 and 2.3, also shows that while the strengths of the concrete for Series V and VII do not conform to those of Series I, II and VI, the standard diviations and range of measured values are comparable for all test series. This indicates that the differences in measured concrete strengths is not the result of differences in the method of testing, but the result of actual differences in the concrete. Therefore, in order to eliminate a questionable variable from the determination of representative curves, only Test Series I, II and VI will be included in these determinations.

In determining a representative curve for the one-in. bonded length, bond force-slip relationship, average values of bond force were calculated from Test Series I and II at several values of slip. In determining the representative curve for the three-in. bond length, bond force-slip relationship, average values of bond force were calculated from Test Series VI at several values of slip. No representative curve was determined for the six-in. bonded length, bond-slip relationship. Plots of these representative curves are shown in Figures 3.9 and 3.10.

A comparison of the calculated bond force-slip relationship with the average experimental bond force slip relationship for the three-in. bond length specimen is plotted in Figure 3.6.

The mean peak bond stress for the one-in. bonded length, knurled wire is 510 psi. The mean peak bond stress for the three-in. bonded length, knurled wire is 500 psi. This suggests that the bond stress remains fairly constant along the bonded length. This is a result of the knurling of the wire. Knurling increases the frictional resistance bond (as explained in Section 3.2) and so maintains the bond stress at a fairly constant level, after the interlocking mechanism has failed.

A fairly close correspondence exists between the calculated and experimental bond force-slip relationships. However, the slope, after the peak bond force is reached, is steeper for the calculated relationship than for the experimental relationship. This discrepancy occurs because the assumption that the one-in. tests represent the actual bond-slip relation is only approximately true. The bond-slip curve of the one-in. test dropped immediately after the initial bond strength was exceeded.

This large drop in bond strength did not occur in tests with larger bonded lengths, but since the calculations were based on the values of the one-in. tests, the calculated relations will reflect this drop.

4. SUMMARY AND CONCLUSIONS

The object of this investigation was to study the bond characteristics of #8 gage steel reinforcing wire embedded in small-scale concrete.

A total of 56 pull-out specimens were tested under the following test schedule:

1 inch bonded length, plain wire: 16 specimens
1 inch bonded length, knurled wire: 16 specimens
3 inch bonded length, knurled wire: 16 specimens
6 inch bonded length, knurled wire: 8 specimens

Bond between steel wire and concrete can be explained in terms of two distinct mechanisms. These are an initial interlocking mechanism followed by a frictional resistance mechanism.

Knurling the wire showed no definite influence on the interlocking mechanism. This is confirmed by comparison of the results of Series I and II with Series III and IV. Knurling does, however, increase the frictional resistance. The increase in frictional resistance tends to increase slightly the bond strength for the one-in. bonded length specimen above the strength of the interlocking mechanism. At this point, the bond-slip curve decreases slightly and then levels off. The significance of this increase in frictional resistance becomes apparent at longer bonded lengths. Because the bond-slip relationship for the one-in. plain wire exhibits a sharp drop in bond stress after the interlocking mechanism has failed, the maximum bond stress should decrease with increasing bonded length. For the one-in. bonded length of knurled wire, the bond-slip curve remains fairly constant once the maximum bond stress has been reached. Therefore, the maximum bond stress should remain constant with increasing bonded length.

The testing of bond strength involves many variables which are difficult to control. The concrete variables include the strength of the concrete, its bleeding characteristics, and the distribution of the aggregates and air voids. The condition of the surface of the steel, such as the depth of the knurl and the variations of the wire diameter, will also affect the results of bond tests. Finally, the alignment of the steel wire in the concrete can influence the results of bond tests. In evaluating the mean bond strength, consideration must be given to the fact that the actual bond strength can deviate significantly from the mean.

The mean bond stress measured in this investigation for the knurled wire, was 550 psi with a standard deviation of 130 psi. The strength of the #8 gage knurled steel wire having a yield stress of 70 ksi should, therefore, be developed in five to seven inches.

Table 2.1 Sieve Analysis

sieve number	size of opening	% retained on sieve fine sand	% retained on sieve coarse sand
	1"	0	0
	3/4"	0	0
	1/2"	0	0
	3/8"	0	0
4	0.187	0	4
8	0.0937	0	12
16	0.0469	0.1	22
30	0.0232	0.3	40
50	0.0117	3.5	84
100	0.0059	80.5	99
Fineness Modulus		0.844	2.61

Table 2.2 Compressive Strength of the Concrete

Test Series	I	II	III	IV	V	VI	VII
Compressive strengths (ksi)	4.14	4.54	3.26	4.70	3.46	3.78	4.42
	4.46	4.98	3.30	4.14	3.70	3.50	4.22
	4.22	4.98	3.38	3.86	3.90	4.18	4.30
	4.58	4.06	3.18	5.17	3.74	4.34	4.18
	4.42	4.54	3.29	4.58	4.06	--	3.82
	--	4.62	--	4.38	4.14	--	--
mean	4.36	4.62	3.28	4.47	3.83	3.95	4.19
standard deviation	±0.18	±0.34	±0.07	±0.45	±0.25	±0.38	±0.22

Table 2.3 Splitting Strength of the Concrete

Test Series	I	II	III	IV	V	VI	VII
splitting strengths (psi)	310	442	219	294	316	295	175
	362	290	322	402	181	414	213
	354	451	292	259	162	336	235
	406	392	207	400	253	348	217
	324	--	--	281	--	--	304
mean	351	394	260	327	228	348	225
standard deviation	±37	±74	±56	±68	±70	±49	±48

Table 3.1 Specimen Material Properties

Test Series	Wire Surface	Bonded Length	Age	f'c(ksi)	fsp (psi)
I	knurled	1"	31 days	4.36	351
II	knurled	1"	32 days	4.62	3.94
III	plain	1"	34 days	3.28	260
IV	plain	1"	33 days	4.47	327
V	knurled	3"	31 days	3.83	228
VI	knurled	3"	34 days	3.95	348
VII	knurled	6"	31 days	4.19	225

Table 3.2 Summary of Peak Bond Forces

	Bond Forces (lbs)						
Specimen #	I	II	III	IV	V	VI	VII
1	-	190	150	175	370	-	840
2	300	248	180	160	600	580	810
3	325	195	210	225	490	635	980
4	300	235	135	260	490	-	720
5	375	345	170	215	570	785	890
6	275	310	140	210	300	760	720
7	325	165	180	220	550	930	1060
8	275	465	192	255	380	930	1250
mean	310	269	170	215	469	770	909
standard deviation	$\pm$35	$\pm$100	$\pm$26	$\pm$30	$\pm$107	$\pm$145	$\pm$181
coefficient of variation	0.11	0.37	.15	0.15	0.23	0.19	0.20

Table 3.3 Summary of Peak Bond Stresses

Specimen #	Bond Stresses (psi)						
	I	II	III	IV	V	VI	VII
1	-	372	294	344	242	-	275
2	587	486	353	314	393	380	265
3	635	382	411	442	321	-	236
4	587	460	264	511	321	-	236
5	733	676	333	422	373	514	291
6	538	607	274	413	196	498	236
7	634	323	353	432	360	609	347
8	538	910	376	501	249	609	409
mean	607	527	331	422	307	504	297
standard deviation	±68	±196	±51	±68	±71	±95	±59
coefficient of variation	0.11	0.37	0.15	.15	0.23	0.19	0.20

Table 3.4 Bond Stresses at a Slip of 0.005 in.

	Bond Stresses (psi)						
	I	II	III	IV	V	VI	VII
mean	540	391	142	340	234	498	257
standard deviation	132	166	22	42	61	88	63
coefficient of variation	0.24	0.42	0.15	0.18	0.26	0.17	0.24

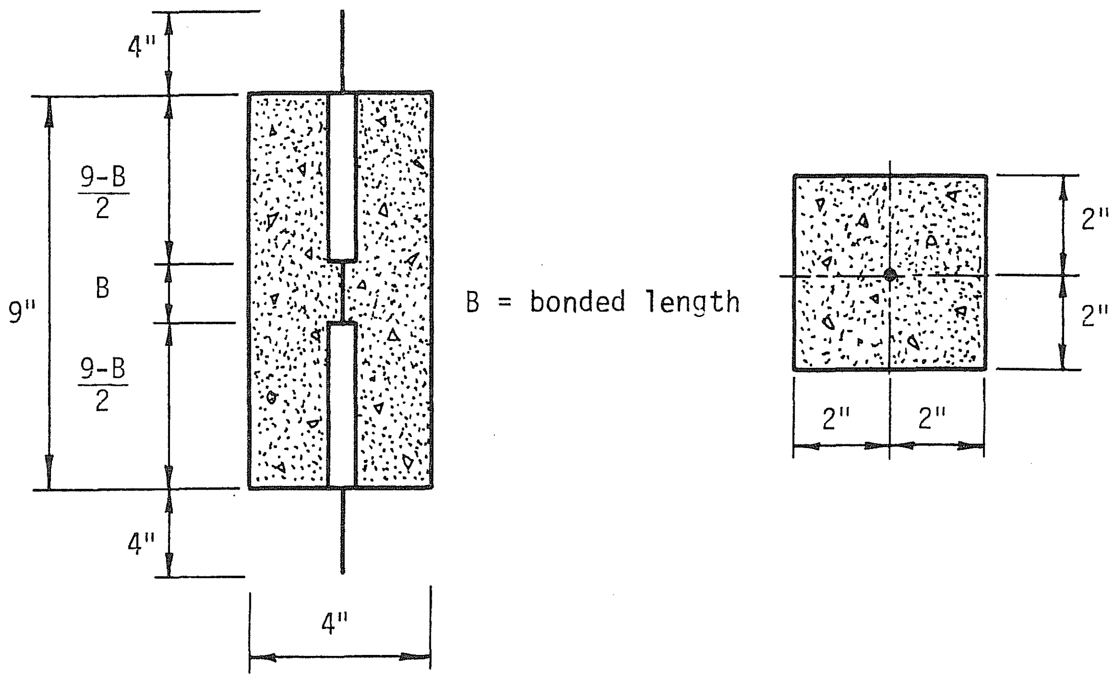

Figure 2.1 Test Specimen

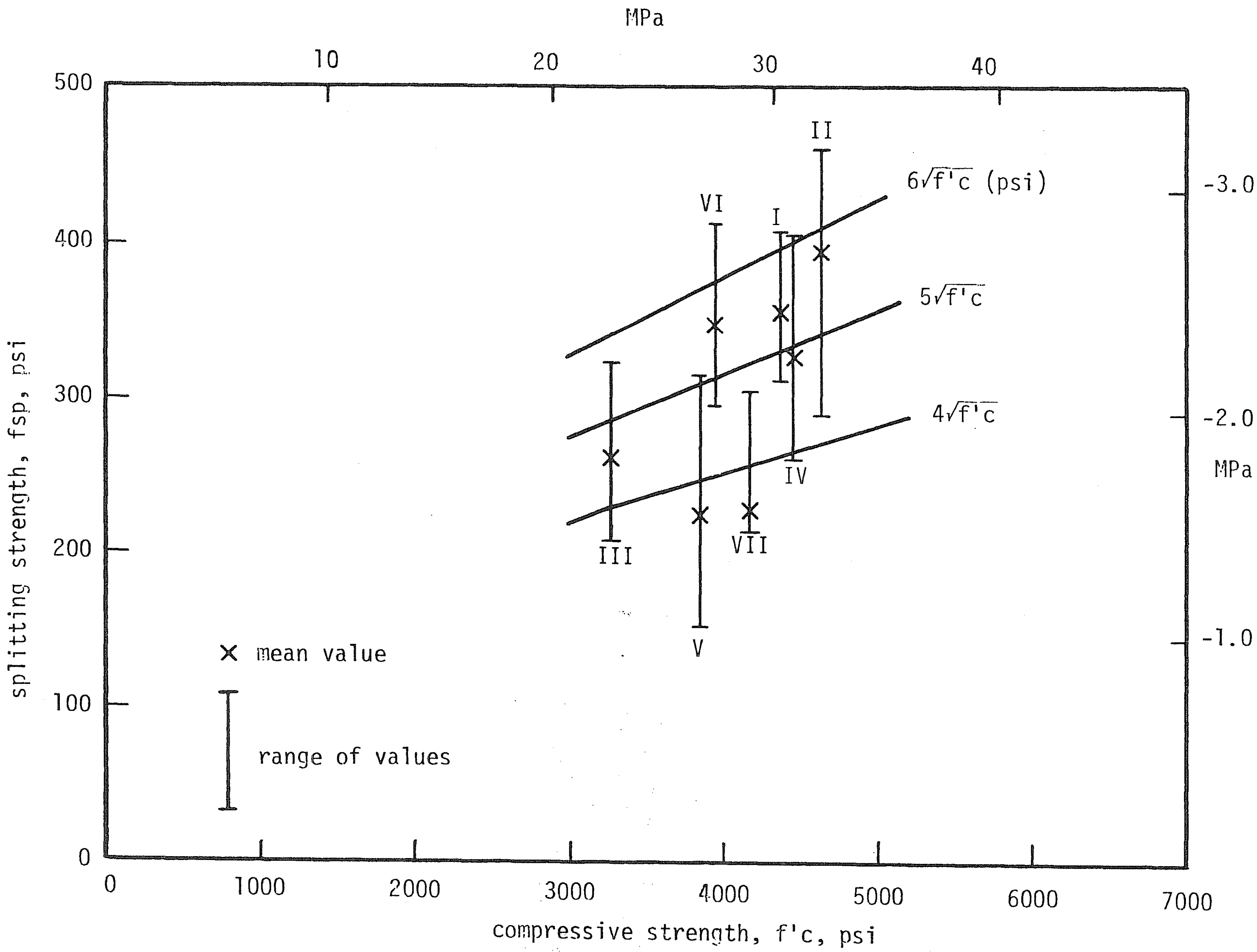

Figure 2.2 Measured Relationship between the Splitting and Compressive Strengths of the Concrete

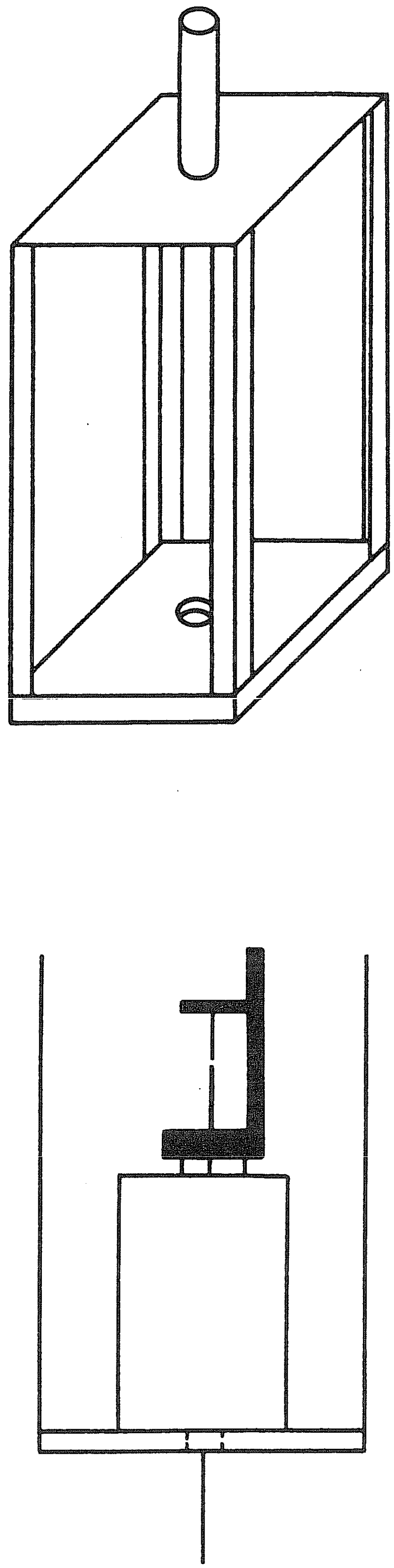

Figure 2.3 Loading Cage

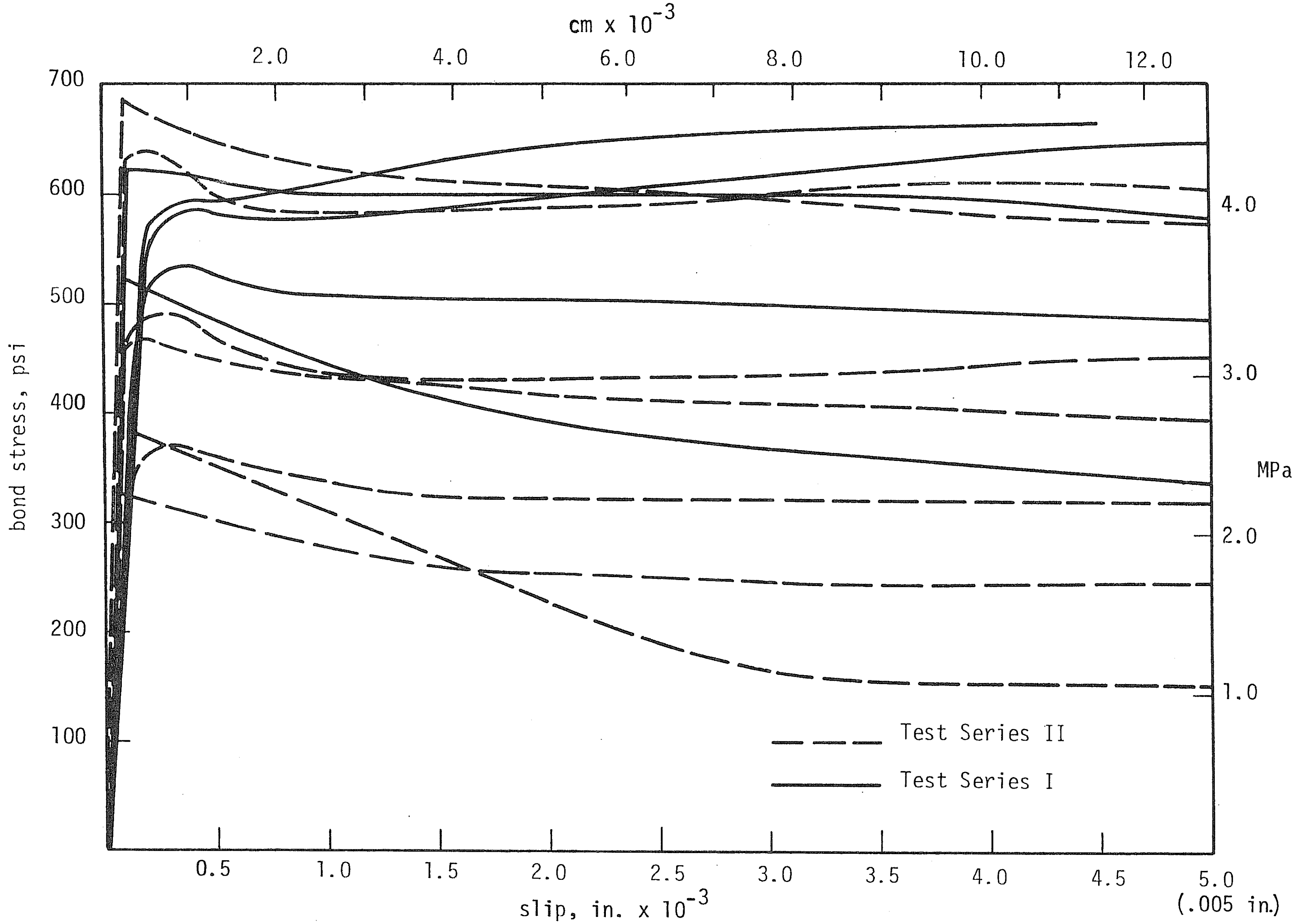

Figure 3.1 Measured Bond Stress - Slip Relationship for a 1-in. Bonded Length, Knurled Wire - Test Series I and II

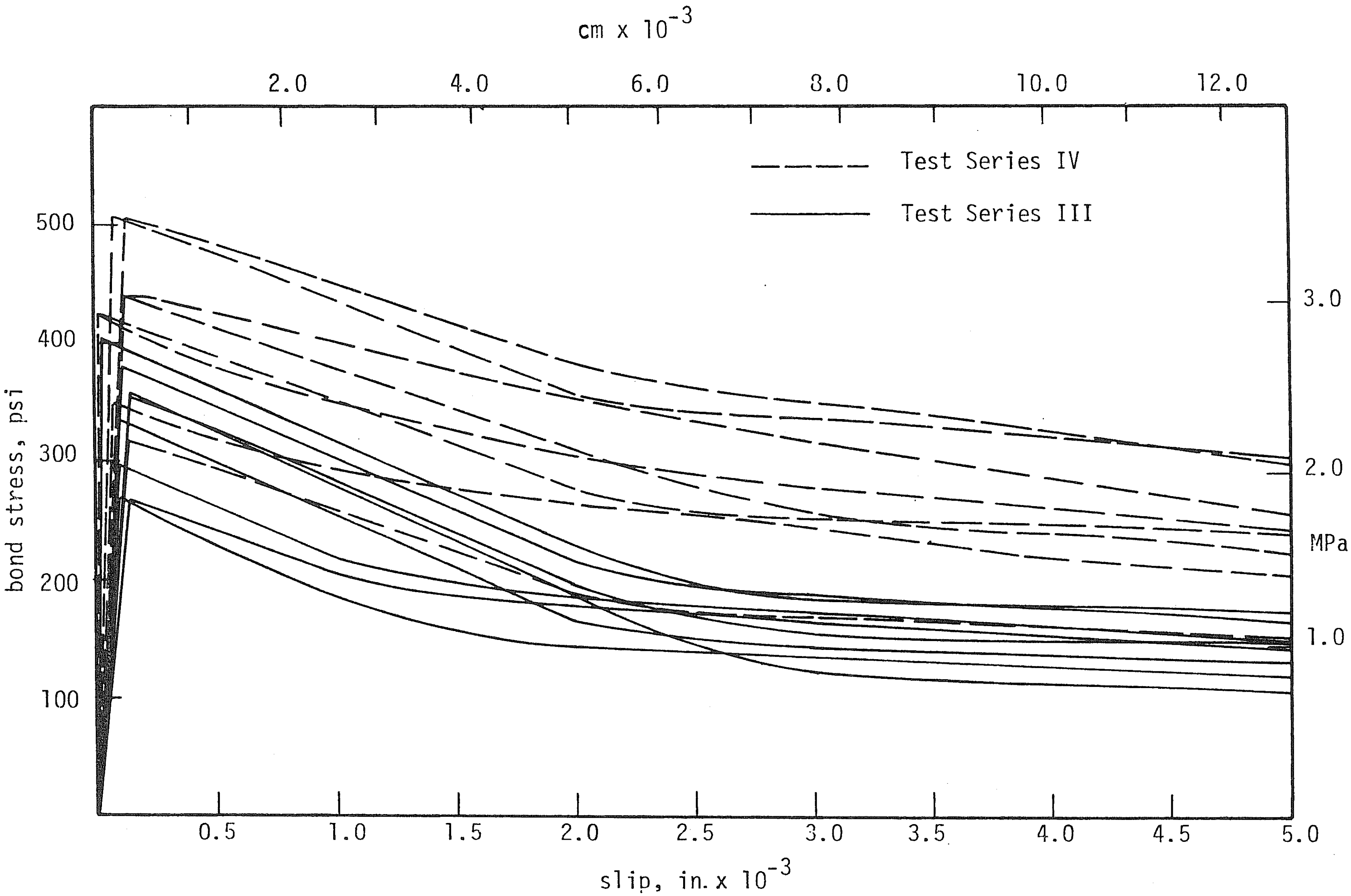

Figure 3.2 Measured Bond Stress - Slip Relationship for a 1-in. Bonded Length, Plain Wire - Test Series III and IV

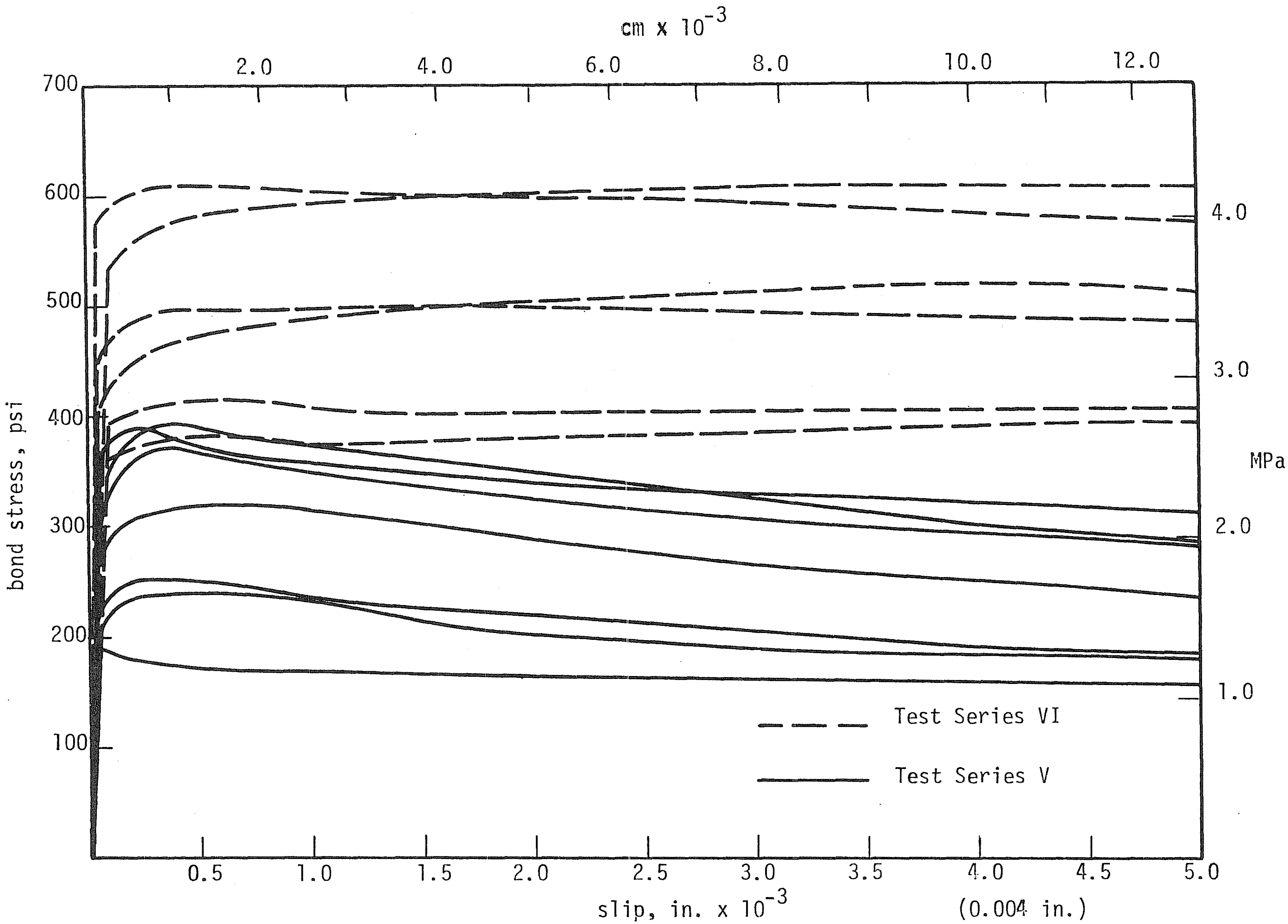

Figure 3.3 Measured Bond Stress - Slip Relationship for a 3-in. Bonded Length, Knurled Wire - Test Series V and VI

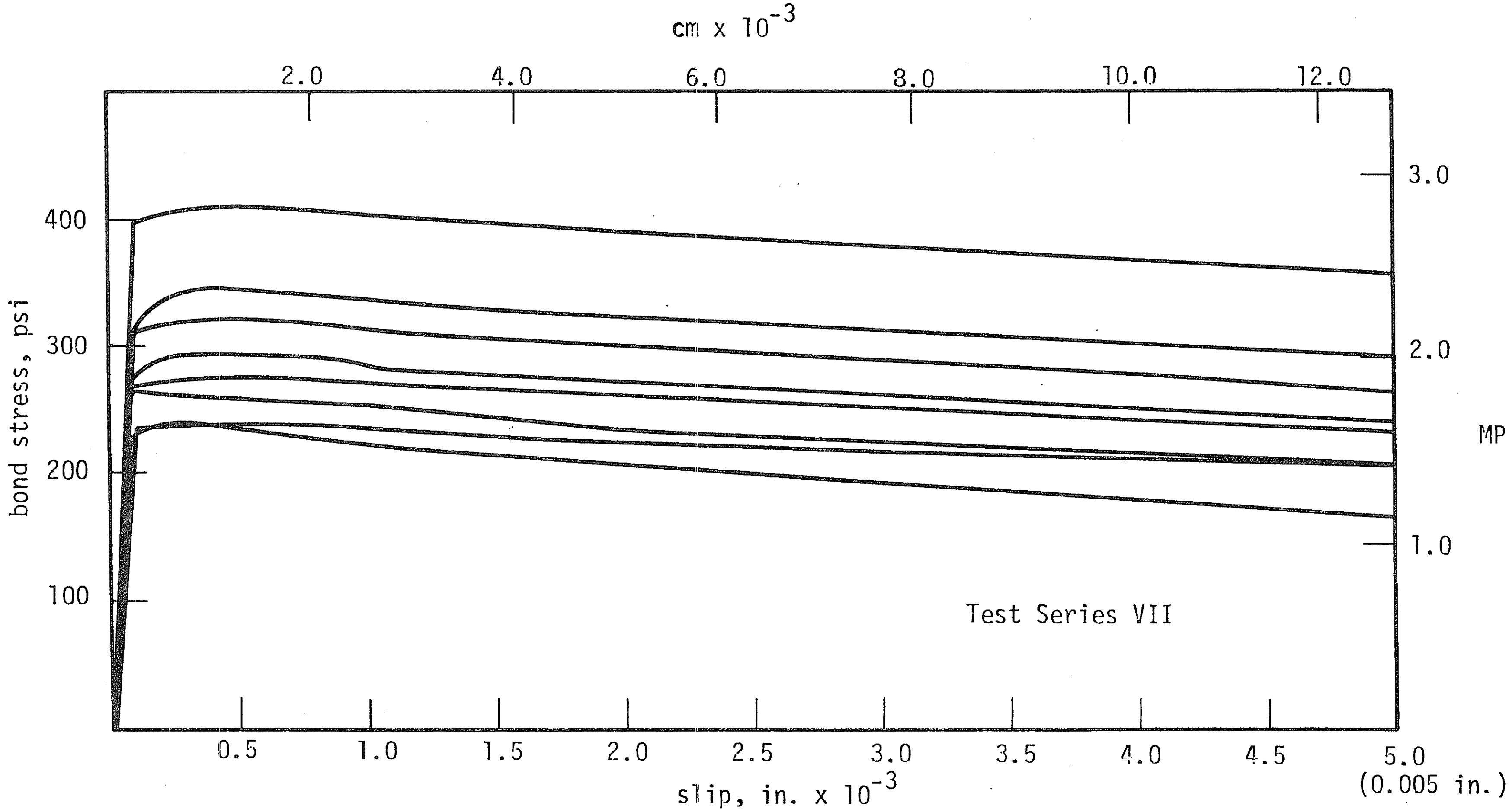

Figure 3.4 Measured Bond Stress - Slip Relationship for a 6-in. Bonded Length, Knurled Wire - Test Series VII

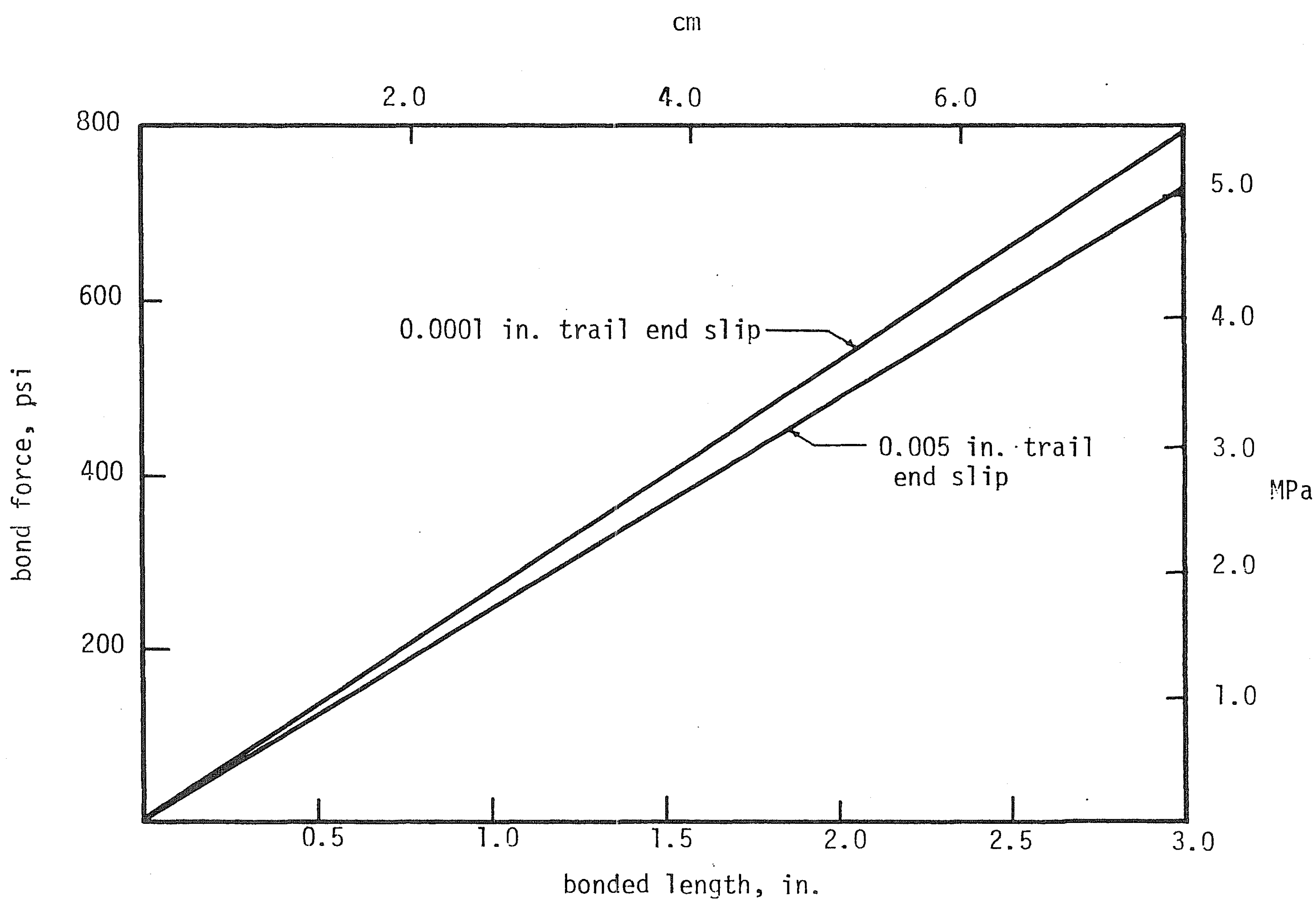

Figure 3.5 Calculated Bond Force - Bonded Length Relationship for Various Trail End Slips

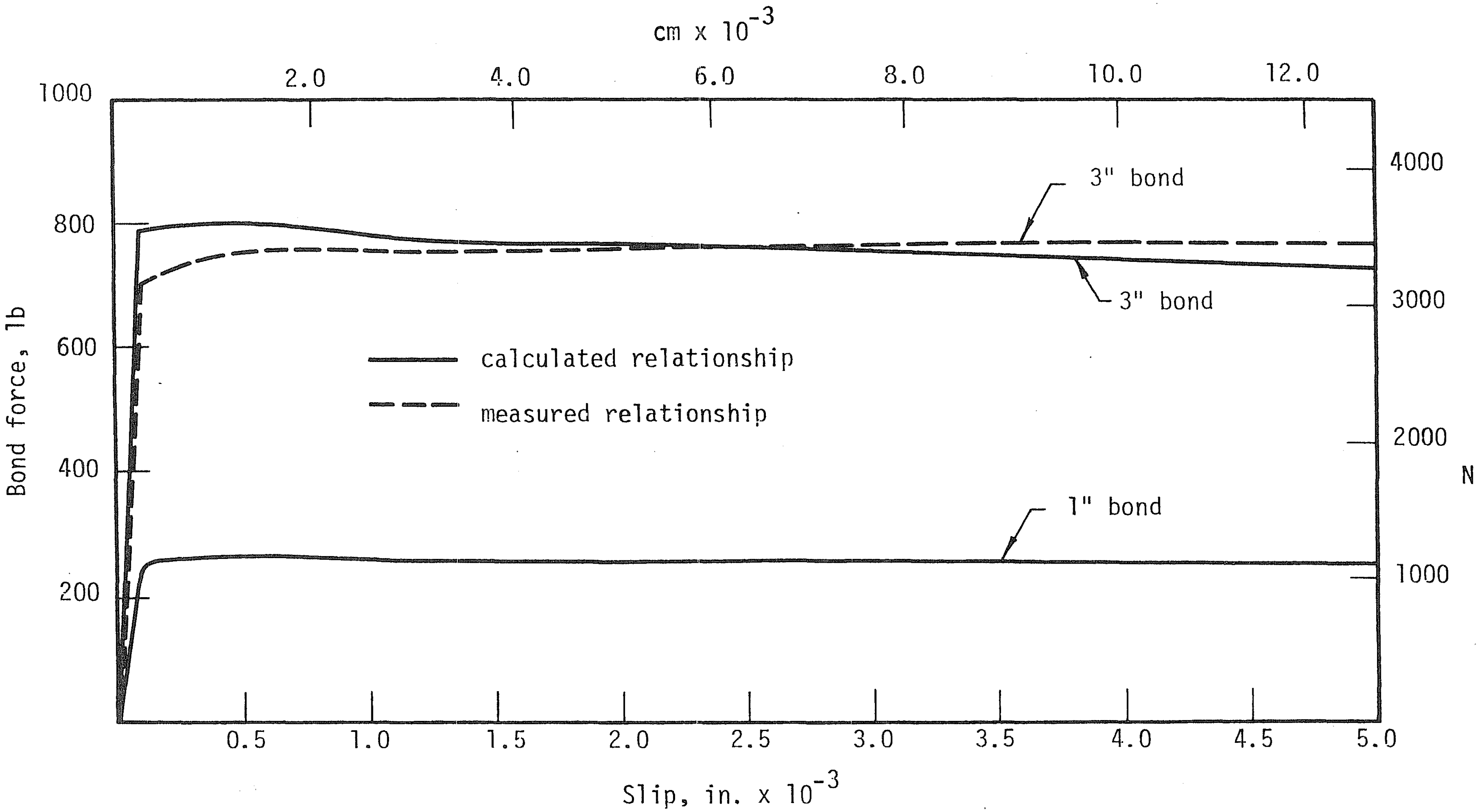

Figure 3.6 Calculated and Measured Bond Force - Slip Relationship for a 3-in. Bonded Length

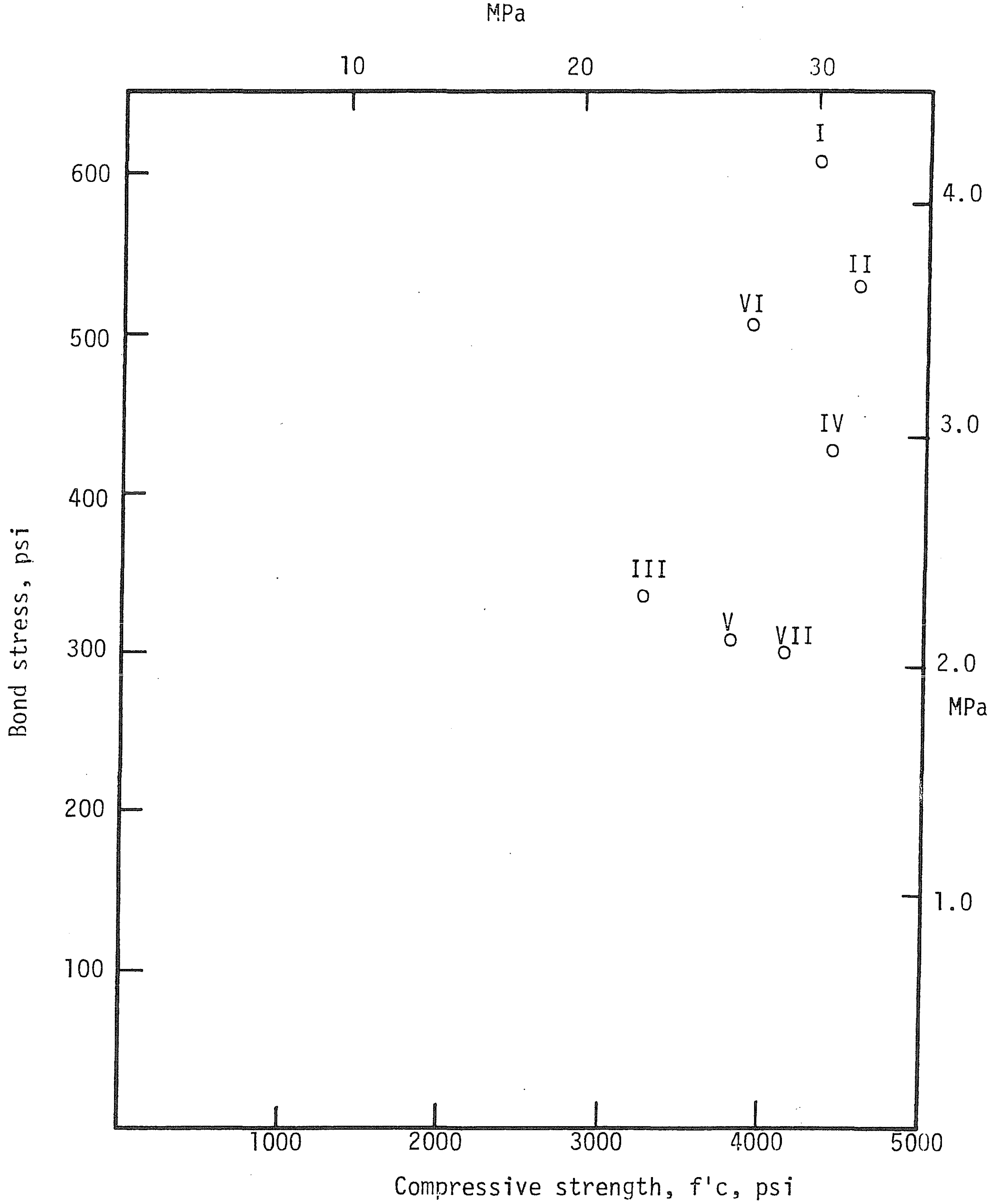

Figure 3.7 Measured Peak Bond Stress vs. Compressive Strength of the Concrete

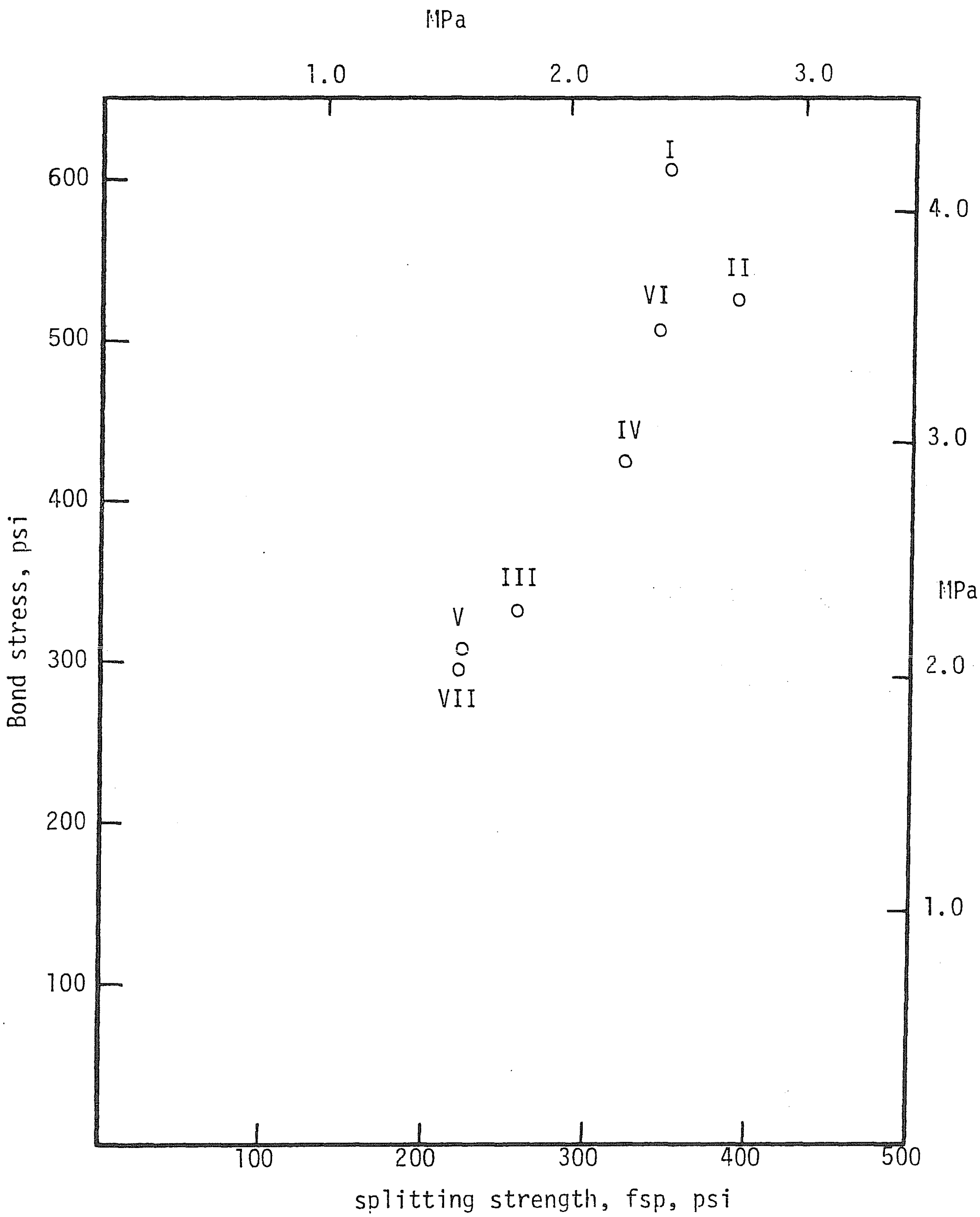

Figure 3.8 Measured Peak Bond Stress vs. Splitting Strength of the Concrete

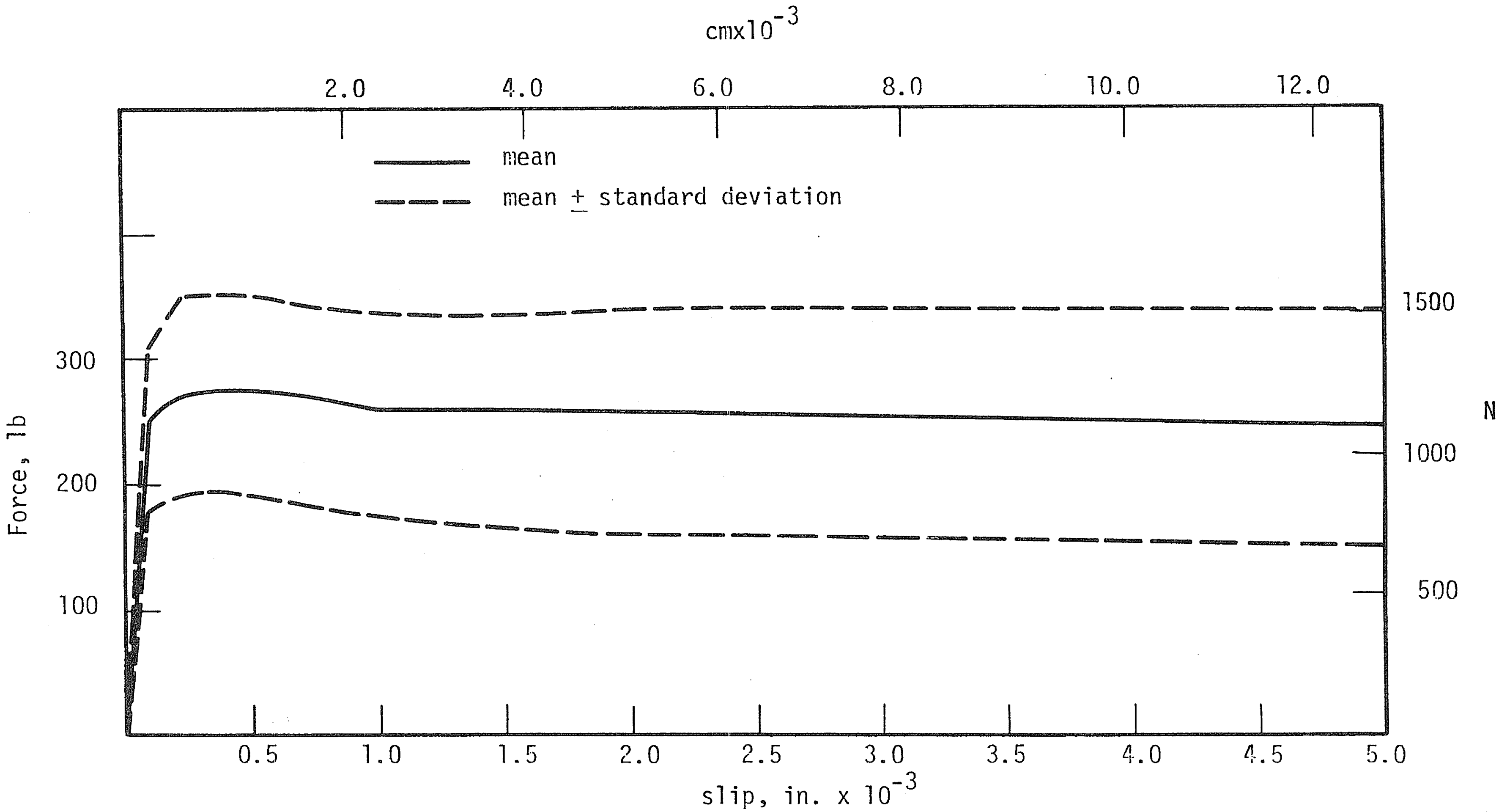

Figure 3.9 Mean Bond Stress - Slip Relationship for a 1-in. Bonded Length, Knurled Wire

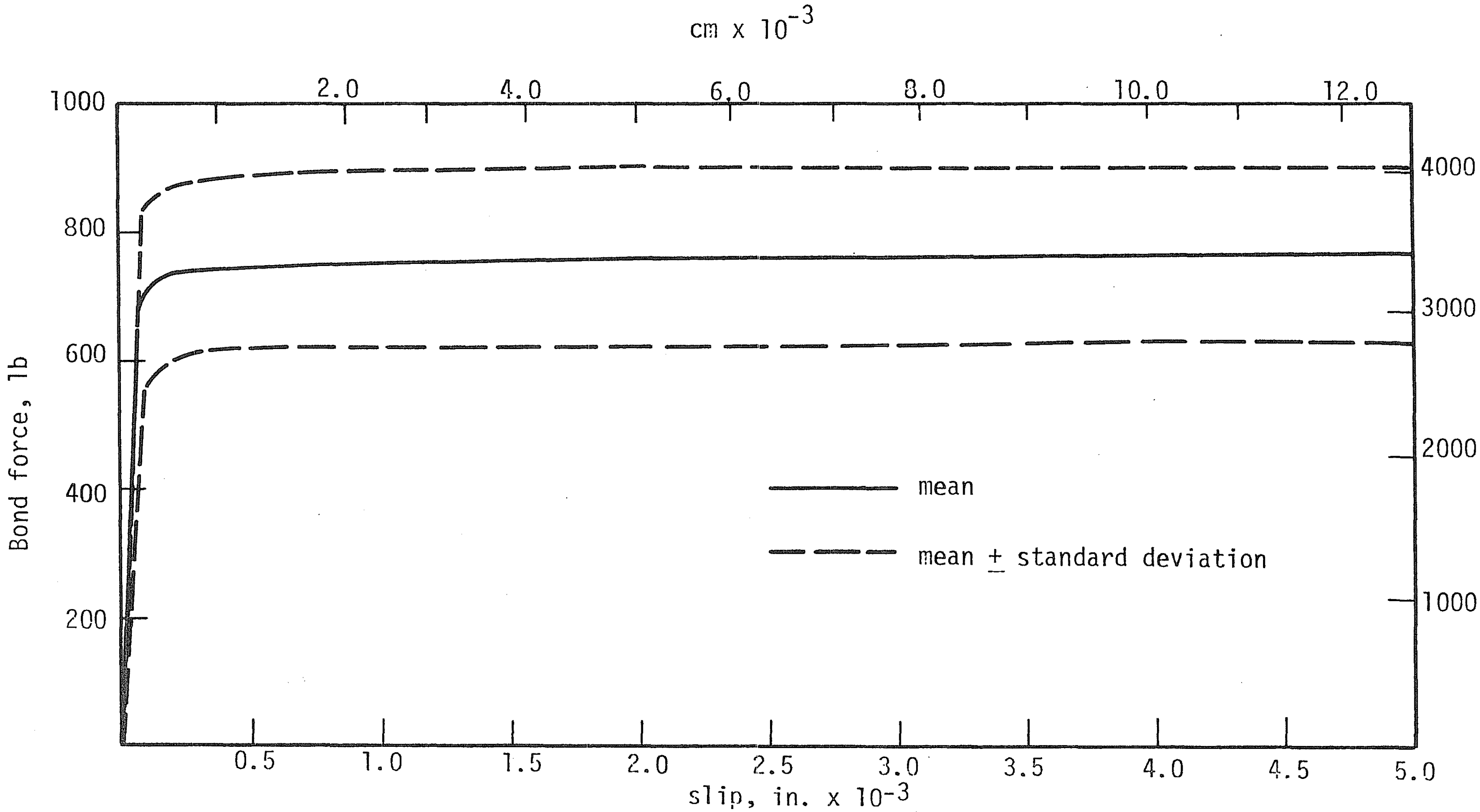

Figure 3.10 Mean Bond Stress - Slip Relationship for a 3-in. Bonded Length, Knurled Wire

APPENDIX A
A Program for Calculating Bond Force-Slip Relationships

APPENDIX A
A PROGRAM FOR CALCULATING BOND FORCE-SLIP RELATIONSHIPS

THIS PROGRAM WAS WRITTEN IN THE BASIC LANGUAGE TO BE USED ON THE DEC SYSTEM 10 COMPUTER OF THE DIGITAL COMPUTER LABORATORY OF THE UNIVERSITY OF ILLINOIS

DEFINITIONS OF THE VARIABLES

L = LENGTH OF ITERATION INTERVAL
E = STRAIN
S = STRAIN
D = SLIP
F = BOND FORCE/INCH
W = TOTAL BOND FORCE
A = CROSS SECTIONAL AREA OF THE WIRE
Y = YOUNG'S MODULUS
X = A COUNTER

PROGRAM

```
100  L=0.5
101  X=1
105  E0=0
200  E1=0.001
300  A=0.02
400  Y=29E6
500  F0=245
600  D0=0.0001
650  W0=0
700  D1=((E0+E1)/2)*L+D0
710 IF D1>0.0001 THEN 740
720 F1=2.45E6*D1
730  GO TO 800
740  IF D1>0.00025 THEN 770
750  F1=245+2E5*(D1-0.001)
760  GO TO 800
770  IF D1>0.0005 THEN 791
780  F1=275
790  GO TO 800
791  IF D1>0.001 THEN 795
792  F1=275-2E4*(D1-0.0005)
793  GO TO 800
795  F1=265-5E3*(D1-0.001)
800  W1=((F0+F1)/2)*L+W0
805  S1=W1*(1/A)*(1/Y)
810  C=ABS((S1-E1)/S1)
820  IF C>0.05 THEN 950
900  PRINT X, "W1=";W1
901  X=X+1
902  IF X>12 THEN 9999
910  E0=E1
920  F0=F1
930  D0=D1
935  W0=W1
940  GO TO 700
950 E1=S1
960  GO TO 700
9999  END
```

References

1. Staffier, S. R., Sozen, M. A., "Effect of Strain Rate on Yield Stress of Model Reinforcement," University of Illinois, Structural Research Series No. 45, Urbana 1975, pp. 8, 48.

2. Stocker, M. I., Sozen, M. A., "Investigation of Prestressed Reinforced Concrete for Highway Bridges, Part V: Bond Characteristics of Prestressing Strand," Engineering Experimental Station, Univ. of Illinois, Bulletin 503, Urbana, 1970, pp. 46-47, 64.

3. Abrams, D. A., "Tests of Bond Between Concrete and Steel," Engineering Experiment Station, Univ. of Illinois, Bulletin 71, Urbana, 1913.